ABUNDANCES IN DAMPED LYMAN-ALPHA SYSTEMS AND CHEMICAL EVOLUTION OF HIGH REDSHIFT GALAXIES

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Abstract. Recent abundance measurements in damped Lyα galaxies, supplemented with unpublished Keck observations, are discussed. The metallicity distribution with cosmic time is examined for clues about the degree of enrichment, the onset of initial star formation, and the nature of the galaxies. The relative abundances of the elements are compared with the abundance patterns in Galactic halo stars and in the Sun, taking into account the effects of dust depletion, in order to gain insight into the stellar processes and the time scales by which the enrichment occurred.

1. Introduction

Without doubt, one of the most significant developments over the last decade in quasar absorption line studies has been the recognition of high-redshift damped Lyα (DLA) absorption systems as the progenitor of present-day galaxies (Wolfe et al 1986) and of their utility for *direct* observational study of the chemical enrichment history of normal galaxies since the very early epoch. Such studies are therefore complementary to the traditional approach to galactic chemical evolution based on studies of stellar populations in the Milky Way and in nearby galaxies (these proceedings). Lauroesch et al (1996) summarized then-existing DLA abundance measurements and discussed their implications for understanding the chemical evolution history of normal galaxies. Results from two new surveys have since appeared in press (Lu et al 1996, hereafter LSBCV; Pettini et al 1997a,b), which represent a significant improvement in quantity and quality over

previous measurements. The Pettini et al studies contain the most measurements of Zn and Cr abundances obtained from high S/N medium resolution (FWHM=30-80 km/s) observations. The Lu et al study was based on high S/N echelle (FWHM=6-8 km/s) observations collected with the Keck I 10m telescope and comprises the single largest source of abundance measurements for other elements (C, N, O, Si, S, Mn, Fe, Ni, as well as Zn and Cr). Our discussion will focus on the new survey results and how they provide new insight on understanding early galactic chemical evolution.

Excellent discussions of various uncertainties that may affect the DLA abundance measurements and interpretations can be found in Lauroesch et al (1996). Since the LSBCV and Pettini et al (1997a,b) surveys used weak lines to derive column densities and elemental abundances, uncertainties resulting from saturated absorption lines should be minimal. Typical measurement uncertainties in the abundances are ~ 0.1 dex. More precise determinations of oscillator strength (f-value) for several important species (e.g., Si II, Fe II, Cr II) have become available recently (see Table 2 of Savage & Sembach 1996 and references therein); the new surveys have adopted these more accurate f-values. The abundance estimates generally assume that the bulk of the absorbing H gas is neutral and that column density ratios of dominant ions in neutral gas to H I yield direct measures of the actual gas-phase abundance of the elements with negligible ionization corrections. This assumption appears to be corroborated by simple ionization models (Viegas 1995, Lu et al 1995; Prochaska and Wolfe 1996).[1]

2. Distribution of Metallicity as a Function of Redshift

Figure 1 shows the distribution of [Fe/H] vs z for the sample of DLA galaxies (open circles). The "$\star$" symbols map out the similar relation for a sample of Galactic disk stars in the solar neighborhood (Edvardsson et al 1993). The DLA data are taken from Table 16 of LSBCV (see LSBCV for references) with the addition of 14 new measurements based on unpublished work of our group and of Wolfe and Prochaska (5 systems). The addition of 7 new measurements at $z > 3$ considerably improves the statistics in this redshift range. Some of the new measurements are still preliminary and may be subject to change in the final analysis. However, the changes (if any) are expected to be small and should have no effect on any of the conclusions. Most existing measurements are for $z > 1.6$; extending the programs to lower redshifts clearly remains a priority. Below we summarize the main conclusions.

[1]Green et al (1995) reported a large ionization correction for the $z = 1.77$ DLA system toward Q 1331+170. Since the claim was based on a N(O I)/N(S II) ratio from saturated O I absorption, the inferred large ionization correction is somewhat suspect.

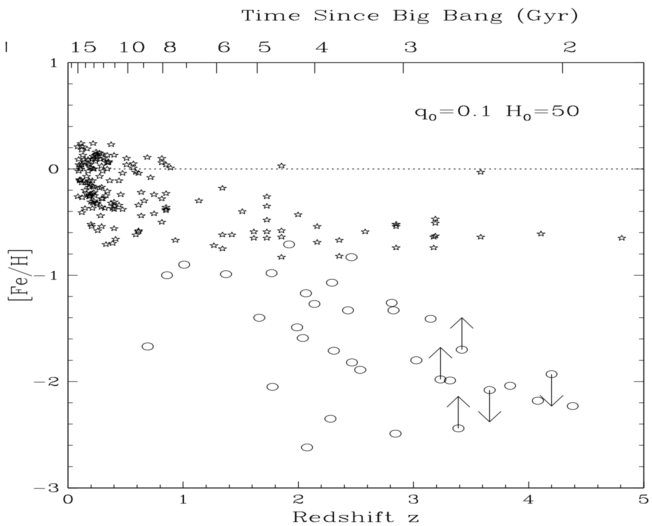

Figure 1. [Fe/H] vs z for damped Lyα systems (open circles) and for Galactic disk stars (star symbols; Edvardsson et al 1993), where [Fe/H]$\equiv$log(Fe/H)$-$log(Fe/H)$_\odot$. The stellar ages have been converted into redshifts for a $q_0 = 0.1$ and $H_0 = 50$ cosmology.

1. Typical DLA galaxies have $-2.5 <$[Fe/H]< -1, corresponding to 1/300 to 1/10 solar metallicity. The N(H I)-weighted mean metallicity is $<$[Fe/H]$>\simeq -1.5$ at $\langle z \rangle = 2.5$. The low metallicities are consistent with them being young galaxies in the early stages of chemical enrichment. If DLA systems eventually evolve to solar mean metallicity at $z = 0$, the low metallicities at $z > 2$ suggest that most of the baryonic matter in the galaxies should be in the gas phase rather than in stars and that most of the star formation should occur at $z < 2$, consistent with results from deep galaxy redshift surveys (cf, Connolly et al 1997). The N(H I)-weighted mean metallicity in terms of Zn is about a factor of 2-3 (0.4 dex) higher (Pettini et al 1997b), possibility suggesting that some of the Fe atoms are locked up in dust grains in the DLA galaxies (section 3).

2. DLA galaxies appear significantly less metal-enriched than the Galactic disk in its past. Taken at face value, this argues against the suggestion that DLA galaxies are high-redshift (proto-) galactic disks (Wolfe 1988). Rather, the metallicities of the DLA systems are more similar to those of globular clusters and nearby dwarf galaxies. This result may be in potential conflict with the evidence that DLA systems appear to show kinematics characteristic of fast-rotating ($v_{rot} \sim 250$ km/s) disks (Prochaska & Wolfe 1997). However, the rotating disk interpretation of the DLA kinematics (Prochaska & Wolfe 1997) may not be the only possible explanation

(Haehnelt, Steinmetz, & Rauch 1997). The significance of the metallicity discrepancy between the DLA galaxies and the Milky Way disk may also be questioned for several reasons. (1) Age determinations for old stars can be quite uncertain. The ages of the stars in Figure 1 at $z > 2$ carry an uncertainty of 2-3 Gyrs from measurement errors alone, and there may also be systematic effects (Edvardsson et al 1993). (2) The true metallicities of DLAs may be higher than that indicated by [Fe/H] if significant dust depletion of Fe has occurred (cf, Pettini et al 1997a). However, this effect alone cannot explain the discrepancy entirely because the inferred depletion of Fe is only ~ 0.4 dex (section 3). (3) DLA systems may preferentially probe regions of disk galaxies (assuming they exist at the relevant redshifts) beyond the equivalent of the solar circle owing to the larger absorption cross section. The metallicity gradient known to exist in local spiral disks (Vila-Costas & Edmunds 1992) then helps to explain the discrepancy (Ferrini, Molla, & Diaz 1997).

3. The mean metallicity of DLA systems clearly increases from $z > 4$ to $z \sim 2$ as expected. However, there is a factor of $\sim$30 scatter in [Fe/H] at $2 < z < 3$, presumably reflecting differences in the formation epoch/star formation history of the galaxies and/or a mixture of morphological types. LSBCV found that the mean metallicity of DLAs increases fairly abruptly at $z < 3$ compared to $z > 3$, which could be interpreted to signal the onset of star formation in DLA galaxies. The much more uniform sampling of the $z > 3$ region now available shows that the change in metallicity from $z < 3$ to $z > 3$ is actually much smoother. The metallicity distribution appears to reach a "plateau" value of [Fe/H]~ -2 to -2.5 at $z > 4$. Coincidentally, this "plateau" metallicity is identical (within the measurement uncertainties) to that found for the intergalactic medium (IGM) clouds at similar redshifts, as inferred from the C IV absorption associated with Lyα forest clouds (Cowie et al 1995; Tytler et al 1995; Songaila & Cowie 1996). This coincidence suggests that the metals in DLA galaxies with [Fe/H]~ -2 to -2.5 may simply reflect those in the IGM, possibly produced by Pop III stars (Ostriker & Snedin 1996). If this interpretation is correct, then significant star formation did not start in DLA galaxies until $z \sim 3-4$. Such an inference is consistent with the decline in the neutral gas content of DLA systems at $z > 3$ (Storrie-Lombardi, McMahon, & Irwin 1996), presumably because DLA galaxies are still being formed at such high redshifts; and with the rapid decline in the space density of quasars at $z > 3$ (Schmidt, Schneider, & Gunn 1995). It will be important to study more DLA systems at the highest redshift possible to confirm the reality of the "plateau" metallicity, and to improve the accuracy of the metallicity determination for IGM clouds, which at present may be uncertain by as much as a factor of 10.

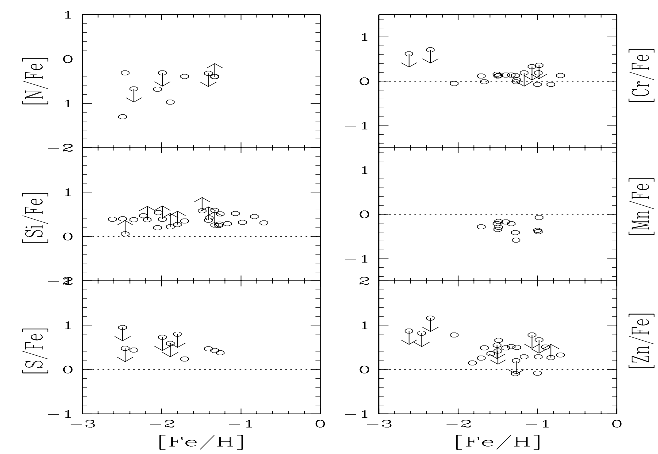

Figure 2. Relative abundance patterns of damped Lyα systems.

3. Relative Abundances

Abundance ratios of elements contain important clues to the stellar processes (SN II, SN Ia, AGB stars) and the time scales by which the elements were produced (Wheeler, Sneden, & Truran 1989). The straightforward conversion from redshift to cosmic time provides an accurate clock to gauge the progress of SN II, SN Ia, and AGB star enrichment, which in turn may be used to calibrate the events that affected Galactic chemical evolution. However, unlike stellar abundances, the abundances derived from interstellar absorption lines may not reflect the total abundance[2] of the elements since most elements are prone to condensation onto dust grains (cf. Jenkins 1987). Consequently, possible dust depletion effects must be taken into consideration in order to reach reliable conclusions.

The abundance ratios to Fe of selected elements are plotted against [Fe/H] of the systems in Figure 2, which represents an updated version of Figure 23 in LSBCV incorporating our unpublished measurements. Other elements are not shown either because of too few measurements (e.g., C, O, Al) or suspicions of inaccurate f-values (Ni; see end of this section). No significant evidence is found for the abundance ratios to change with redshift over $z = 1.6 - 4.4$. The DLA abundance patterns are clearly different from the solar pattern. Since the DLA galaxies at $z = 2 - 4$ are at an epoch when the Galactic halo was formed, they may be expected to show sim-

[2]We use *total abundance* or *intrinsic abundance* interchangeably to indicate the abundance of an element in both the gas phase and dust grains.

ilar intrinsic abundance patterns to those observed in halo stars. Indeed, the DLA abundance patterns are very similar to that seen in Galactic halo stars[3] and globular clusters (Wheeler et al 1989), showing a low N/Fe ratio, an overabundance of Si and S relative to Fe (i.e., enhancement of α-process elements over Fe-group elements), and an underabundance of Mn relative to Fe (i.e., the odd-even effect). The similarities suggest that metal productions in most of the DLA systems under study were probably dominated by massive stars via SN IIs. However, the super-solar Zn/Fe ratios in DLA systems, $<$[Zn/Fe]$>\simeq$ 0.4 dex, are inconsistent with the abundance patterns seen in halo stars, where Zn/Fe$\simeq$solar for all stars with [Fe/H]> -3 (Wheeler et al 1989). Super-solar Zn/Fe ratios are often found in Galactic ISM clouds because, while Zn is relatively unaffected by dust, 80-99% of the Fe atoms are usually removed from the gas phase by condensation onto dust grains (Jenkins 1987). The super-solar Zn/Fe ratios in DLAs are likely caused by the same dust depletion effect (Meyer & Roth 1990; Pettini et al 1994;1997a).

Many attempts have been made to compare the DLA abundance patterns with the solar pattern and the halo-star pattern for consistency, assuming dust grains in DLA systems are the same as Galactic dust (LSBCV; Lauroesch et al 1996; Kulkarni, Fall, & Truran 1997; Welty et al 1997; Vladilo 1997). Despite the efforts, however, no clear picture has emerged. LSBCV noted the close resemblance between the DLA abundance patterns and the halo-star pattern but found it difficult to interpret the "anomalous" Zn/Fe ratios in DLA systems as the consequence of dust depletion since it would have problem explaining some other abundance ratios (e.g., N/Fe, Mn/Fe); they suggested that the supersolar Zn/Fe ratios may be intrinsic to the nucleosynthesis. Lauroesch et al (1996) also found evidence for a halo-star-like abundance pattern and argued that, since the magnitudes of nucleosynthesis effects and dust depletion effects can be comparable, an unambiguous statement concerning the extent of dust depletion in DLA systems is not yet possible. Welty et al (1997) found similar evidence for a halo-star-like pattern and concluded that the DLA abundance patterns are affected by both nucleosynthetic effects and dust depletion - to different degrees for different systems. Kulkarni et al (1997), on the other hand, concluded that the DLA abundances are equally well explained with a solar+dust depletion or a halo-star pattern, but acknowledged that neither provides a perfect match to the data. Vladilo (1997) took a somewhat different approach. Assuming DLAs have solar intrinsic Zn/Fe and Zn/Cr ratios and contain Galactic-type dust, he used the observed Zn/Fe or Zn/Cr ratios to infer the dust-to-metal ratio appropriate for each DLA system

[3]In this discussion, Galactic *halo stars* refer to those with [Fe/H]< -1.

which then allows him to predict the amount of each element this is in dust grains. The inferred total abundances of the α-elements and Fe-group elements showed abundance ratios within 0.2 dex of the solar ratio (see Figure 1 of Vladilo 1997), thus suggesting no evidence for α-element enhancement over Fe-group elements that is characteristic of halo stars.

One common finding by all studies was that DLAs do not exhibit the heavy dust depletion seen in Galactic cool disk clouds. When dust was advocated, the inferred depletion pattern was more similar to that seen in warm disk clouds or warm halo clouds, where the degree of dust depletion is much less than that observed in cool disk clouds (Savage & Sembach 1996). Welty et al (1997) also found that DLA abundance patterns are similar to that seen in the ISM of the SMC. The dust-to-metal ratios inferred for the DLA systems are typically 0.4-0.8 times the Galactic value if the depletion pattern in warm disk clouds is adopted as the reference, and the corresponding dust-to-gas ratio is in the range of 2-25% of the Galactic value (Kulkarni et al 1997; Pettini et al 1997a; Vladilo 1997). These values are similar to that found by Pei, Fall, & Bechtold (1991) based on a comparison of the colors of quasars with and without DLA absorption in their spectra.

Except for LSBCV, none of the previous discussions of DLA abundance patterns included N in the analysis. LSBCV noted that the few then-existing N abundance measurements cast doubt on the dust-depletion interpretation of the Zn/Fe ratios in DLA systems. We have since obtained additional N measurements to examine this issue more closely. Figure 3 (left panels) shows the *inferred* intrinsic abundance patterns of DLAs after accounting for the elements in dust grains following the prescription by Vladilo (1997)[4]. The two DLA systems listed in Table 1 are not included in this analysis since neither shows any evidence for dust. The observed gas-phase abundance of N in the ISM is $[N/H] \simeq -0.2$ with little variations from sightline to sightline (Hibbert, Dufton, & Keenan 1985). As was for other elements considered in the Vladilo model, we assumed in the above analysis that the sub-solar N abundance in the ISM is due to dust depletion despite evidence against such an interpretation (e.g., Mathis 1996 and references therein; see next paragraph). Interestingly, the results show neither a solar pattern (N abundances being too low) nor a halo-star pattern (no obvious α elements enhancement over Fe-group elements). The deviations from the solar ratios in Si/Zn, S/Zn, and Mn/Zn, though small, appear to be systematic.

Recent observations suggest that the *intrinsic* abundances of C, N, O, and Kr in the present-day solar-neighborhood ISM are about 2/3 solar rather than solar (Hibbert et al 1985; Cardelli et al 1996; Sofia et al 1997;

[4]More N abundance measurements exist (Lu, Sargent, & Barlow 1998) but cannot be displayed in Figure 3 owing to lack of measurements of the corresponding Zn abundance.

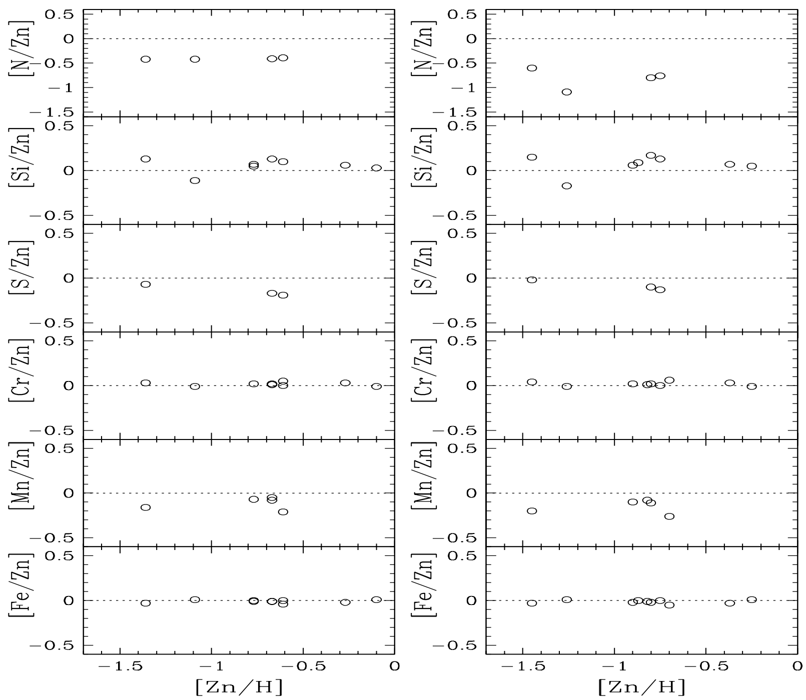

Figure 3. Inferred intrinsic abundance patterns of DLA systems for two different choices of depletion patterns (see text).

Cardelli & Meyer 1997), consistent with abundances in young disk stars (see Snow & Witt 1996 and references therein). This result has significant implications for the compositions of Galactic dust grains (Sofia, Cardelli, & Savage 1994; Snow & Witt 1996; Mathis 1996), which were previously derived assuming solar abundances for the present-day ISM. To examine the consequences of this result for the DLA abundances, we re-derived the depletion pattern appropriate for warm disk clouds (Table 6 of Savage & Sembach 1996) assuming an intrinsic abundance of 2/3 solar for *all* elements, and repeated the above analysis. It turns out the results (Figure 3, right panels) are little changed except for N. This is because, while the depletion pattern for the warm diffuse clouds is significantly changed with the adoption of the new reference abundances, the scaled depletion pattern at the dust-to-metal ratios appropriate for the DLA systems is little affected. The result for N changed significantly because N is no longer depleted with the adoption of the new reference abundances.

Can the inferred intrinsic abundance patterns shown in Figure 3 be

TABLE 1. Damped Lyα Systems Showing No Evidence For Dust

QSO	z_{DLA}	[Fe/H]	[Si/Fe]	[Cr/Fe]	[Mn/Fe]	[Ni/Fe]	[Zn/Fe]
0454+0356[a]	0.8598	−1.00	...	−0.07	−0.36	...	−0.08
1946+7658[b]	1.7382	...[b]	+0.25	+0.13	−0.41	−0.44	−0.09

[a] This system has log$N$(H I)=20.76. The abundances are from LSBCV and Steidel et al 1995. [b] This system is inferred to be a damped Lyα system even though the actual N(H I) of the system is unknown (LSBCV). The abundances are from our unpublished Keck observations except for Mn, which is from Lu et al 1995. These values supersede those in LSBCV based on data with lower S/N.

understood with conventional chemical evolution scenarios? Galactic halo stars show α/Fe=2-3 times solar, which is thought to be the result of SN II enrichment (Wheeler et al 1989). It is generally believed that significant contributions from SN Ia are required in order to reach solar α/Fe ratio. However, the injection of large amounts of primary N into the interstellar medium from intermediate mass stars (3-8 $M_\odot$) during the AGB phase (Renzini & Voli 1981), which must occur before making SN Ia, should raise the N/Fe-group and N/α ratios to nearly solar values, contrary to observations. Having galactic winds carrying away some of the SN IIs ejecta to reduce the α-element abundances will not help since a proportional amount of the Fe-group elements will presumably be removed also, leaving the α/Fe-group ratio in the system unchanged.

Given this situation, it seems appropriate to examine other possibilities. We consider the following alternatives: (1) the properties of dust grains in DLA systems may be different from Galactic dust; or (2) the nucleosynthetic history of DLA systems may be different from that of the Milky Way galaxy. The first possibility seems quite likely since dust grains in the Magellanic Clouds are known from the extinction curves to be different from Galactic dust and from each other. More precise determinations of the dust depletion properties in the Magellanic Clouds' gas (e.g., Welty et al 1997) may provide useful clues. There is also evidence that the second possibility may not be true in the general sense. Two DLA systems are known to have near-solar Zn/Fe ratios (Table 1), indicating the *absence* of dust by common criteria. Yet, the systems show sub-solar Mn/Fe ratios and super-solar Si/Fe ratios; both characteristic of Galactic halo stars (Wheeler et al 1989). Interestingly, one of the systems has Ni/Fe ratio that is a factor of 2.8 below solar, while halo stars show nearly solar Ni/Fe ratios. This difference could be real, or, more likely, it may be due to a systematic error in the Ni II f-values (LSBCV). Detailed studies of such systems should provide important clues to the intrinsic abundance patterns of DLA galaxies.

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